The Canadian Smoke Newsletter

2014

"Connecting diverse terrestrial, emissions, air quality and modelling communities."

Stereoscopic Retrieval of Smoke Plume Heights and Motion from Space-Based Multi-angle Imaging, using the MISR INteractive eXplorer (MINX)

by David L. Nelson[1] and Ralph A. Kahn[2]

[1] Raytheon Company, Pasadena, CA 91101, USA; E-Mail: David.L.Nelson@jpl.nasa.gov; Tel.: 818-393-7641
[2] NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA; E-Mail: Ralph.Kahn@nasa.gov

Introduction

Airborne particles – desert dust, wildfire smoke, volcanic effluent, urban pollution – affect Earth's climate as well as air quality and health. They are found in the atmosphere all over the planet, but vary immensely in amount and properties with season and location. Most aerosol particles are injected into the near-surface "boundary layer," but some, especially wildfire smoke, desert dust and volcanic ash, can be injected higher into the atmosphere, where they can stay aloft longer, travel farther, produce larger climate effects, and possibly affect human and ecosystem health far downwind. For these reasons, monitoring aerosol injection height globally can make important contributions to climate science and air quality studies.

The Multi-angle Imaging Spectro-Radiometer (MISR) is a spaceborne instrument designed to study Earth's clouds, aerosols, and surface. Since late February 2000 it has been retrieving aerosol particle amount and properties, as well as cloud height and wind data, globally, about once per week. The MINX visualization and analysis tool complements the operational MISR data products, enabling users to retrieve heights and winds locally for detailed studies of smoke plumes, at higher spatial resolution and with greater precision than the operational product and other space-based, passive remote sensing techniques. MINX software is being used to provide plume height statistics for climatological studies as well as to investigate the dynamics of individual plumes, and to provide parameterizations for climate modeling.

MISR

In December 1999 NASA launched the TERRA satellite into Earth polar orbit. TERRA is the first of several large platforms in the Earth Observing System (EOS) fleet that are designed to study climate. The Terra satellite hosts five scientific instruments, including MODIS (Moderate Resolution Imaging Spectroradiometer), a familiar legacy instrument, and MISR (Diner et al., 1998), one of the first spaceborne instruments to acquire data globally using multiple cameras to view the Earth at multiple angles (Fig. 1).

Each of MISR's nine cameras images Earth roughly from pole-to-pole, north to south on the day-side, in four spectral channels, centered at blue, green, red and near-infrared wavelengths. Orbits always cross the equator around 10:30 AM and PM standard local time. At 50° N, overpasses occur at about 11:15 AM in

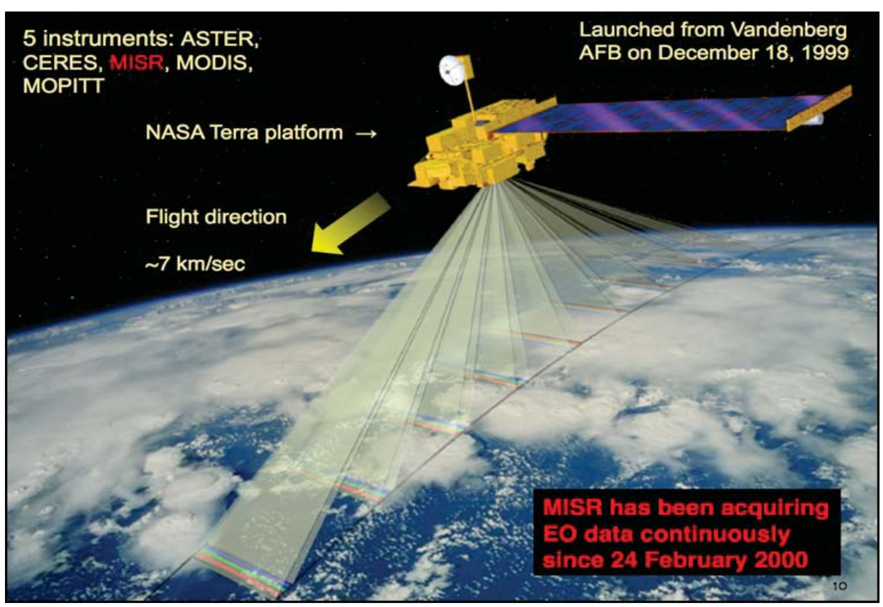


Figure 1. Illustration of the TERRA satellite with MISR aboard, and the nine-camera, four-wavelength MISR observing pattern. TERRA orbits at an altitude of 705 km and completes each orbit in 99 minutes.

most places. The additional time results from TERRA's tilted orbit, which causes a time zone to be crossed. Time zones that do not follow geographic meridians can be exceptions to these rules.

The nine camera zenith angles range from 70° looking forward, through nadir, to 70° looking aft, along the satellite ground track. This allows MISR to view every scene nine times within about seven minutes. The images have a pixel footprint of 275 m in 12 MISR channels and 1100 m in the remaining 24; all four spectral bands in the nadir camera and the red bands in the other eight cameras are acquired at the higher resolution. Global coverage is acquired every 9 days at the equator and every 4 days at 50° N.

Part of MISR's mission is to study clouds by retrieving their heights and motion vectors. Multiple viewing angles provide the capability to apply purely geometric, stereoscopic methods to this task. MISR heights are independent of radiometric calibration uncertainties and detailed knowledge of the atmospheric temperature structure required by instruments that rely on thermal infrared spectral bands to estimate feature height. MISR products can be downloaded from NASA's Atmospheric Sciences Data Center website (https://eosweb.larc.nasa.gov/order-data).

MINX

MISR's operational cloud height and wind products are generated automatically and are used primarily to provide global statistics for climate studies. The MINX software complements the operational product, taking advantage of human-in-the-loop analysis, and making it possible to tease out fine detail from smoke plumes and other features. Beginning in 2006, our group at JPL was funded by the EPA and NASA to develop the MISR Plume Height Project. It aimed to provide a wildfire-smoke-injection-height climatology to support climate change and air quality studies. This required a new approach to retrieving heights. MINX is our solution (Nelson et al., 2013).

MINX is an interactive, GUI-based program that displays a large viewing window in which the nine camera images from a portion of a MISR orbit can be displayed in an animation loop using conventional play/pause movie controls (Fig. 2).

Displaying successive camera images enables the user to study the 3D context of a scene and to detect relationships that would be difficult to discern in a single, nadir-view image. The animation window is also the workspace where a user digitizes a polygon, inside which heights and winds are retrieved on a grid of regularly spaced points. MINX is freely downloadable from the Open Channel

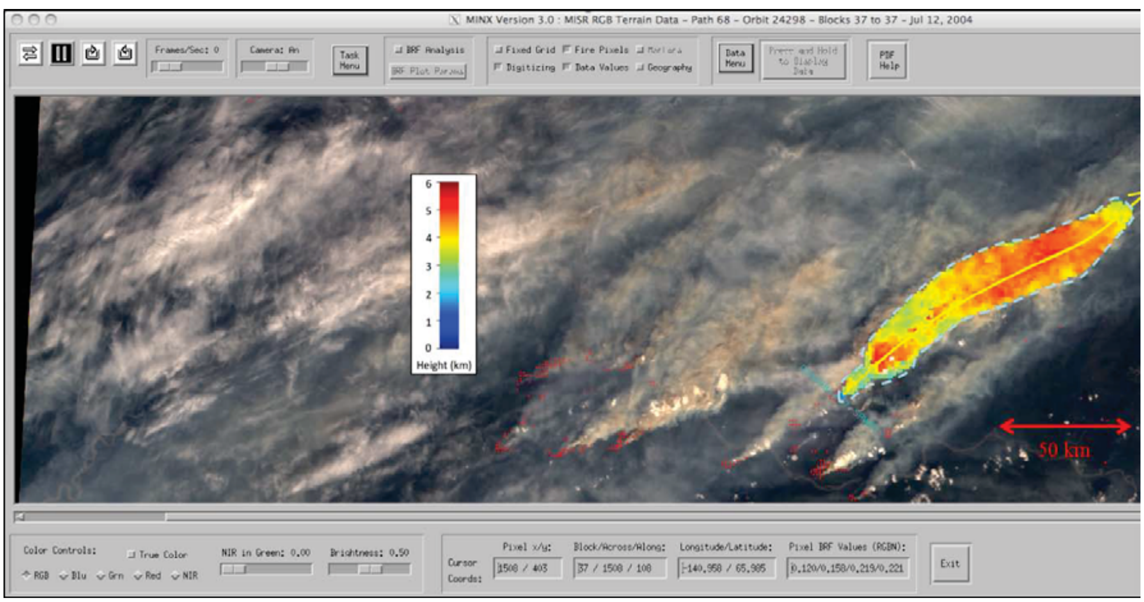


Figure 2. The MISR nadir camera image for orbit 24298 in the image pane of the MINX animation window after one block of MISR data has been loaded. The wildfire plumes on the right half of this image were captured over eastern Alaska on 12 July 2004. Five plumes in the image are associated with fires each producing from 3 to 6 gigawatts of radiative power as measured by MODIS. MODIS thermal detections are shown as red dots; MINX heights above sea level within the plume itself, between about 3 and 5 km, are represented according to the color bar; the dashed, aqua outline of the plume polygon and the yellow wind direction arrow were digitized manually.

Foundation website (https://www.openchannelsoftware.com/projects/MINX).

Retrieving heights stereoscopically from a smoke plume in a MISR scene depends on measuring the parallax observed between pairs of camera images, using an image-matcher. Then applying our knowledge of camera view angles, the height can be computed. This is complicated by the fact that the feature can move due to wind action; in the observed plume displacement, proper motion is conflated with apparent motion due to parallax. Our algorithms separate the contributions from true motion and parallax to produce heights as well as components of wind speed in both the along-swath direction and normal to it. One critical MINX innovation is the requirement that a human provide the wind direction. This reduces the problem of determining three unknowns at every point (height, wind speed along swath and wind speed across) to two and greatly improves retrieval precision (see Nelson et al., 2013, for details). The wind direction can usually be inferred, especially when a fire source is identified as a high-brightness-temperature anomaly in a MODIS thermal-infrared image, and it can be digitized at the same time as the polygon outlining the plume is defined.

All MISR cloud-height products and all versions of MINX before 2014 use MISR's red-band images to generate heights. Red-band retrievals are most successful when the background scene is dark in that spectral band (e.g. plumes over ocean or boreal forest), and when the aerosol being analyzed is optically dense. When one or both of these conditions are not met (e.g. thin plumes over grassland), the red-band might not see the smoke, or not detect the smoke at the highest level. A version of MINX to be released near the end of 2014 will greatly improve the retrieval of thin aerosols over bright surfaces, by using a combination of the red and blue bands in retrievals.

The MISR MINX Plume-Height Project

For the MISR Plume-Height Project, we initially retrieved heights for about 3,400 smoke plumes over North America over five years, 2002 and 2004-2007 (Val Martin et al., 2010). This database of smoke plume heights has since expanded to include about 5000 plumes over North America for fire years 2001-2008, and more than 6500 plumes from other selected regions of the world. A small dataset of 85 plumes was also separately acquired to support the ARCTAS field campaign over Canada in 2008. All these data are available at http://misr.jpl.nasa.gov/getData/accessData/MisrMinxPlumes, in both graphical and digital form.

We are currently digitizing plumes for the entire world for the year 2008, and expect to make these data available before the end of 2014. This should add more than 15,000 smoke plumes to the database. A small number of volcanic plumes are also available on the website, and this is an area that will be expanded in the future.

When using the data on the Plume-Height Project database, several factors should be taken into account. First, the MISR swath seen by all cameras is about 380 km wide, significantly smaller than the MODIS swath. Therefore any location at 50° N latitude is observed by MISR once every four days on average, so many short-lived fire events are not seen by MISR. Second, plumes are seen only in late morning, before some fires have reached their maximum intensity. Third, only red-band retrievals are available for plumes digitized before 2014, so optically thin plumes might be underrepresented, or their heights might be underestimated. The global plume-height retrievals covering 2008 will be the first dataset to use the new red-and-blue-band algorithm. Additional information is available on the plume project website (Fig 3).

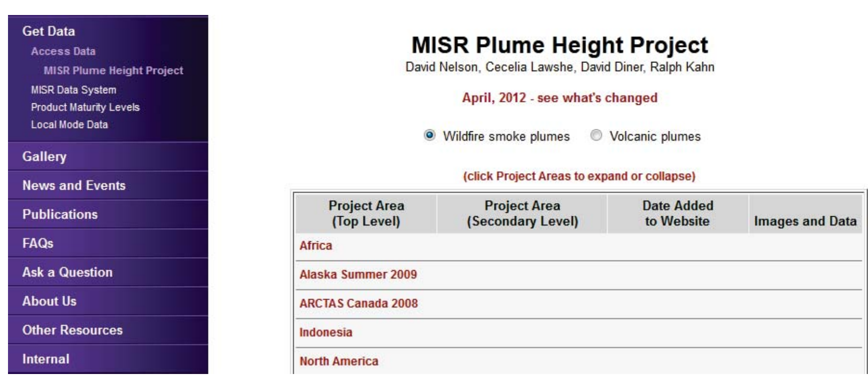


Fig 3. A portion of the project website at http://misr.jpl.nasa.gov/getData/access-Data/MisrMinxPlumes

The Canadian Smoke Newsletter

2014

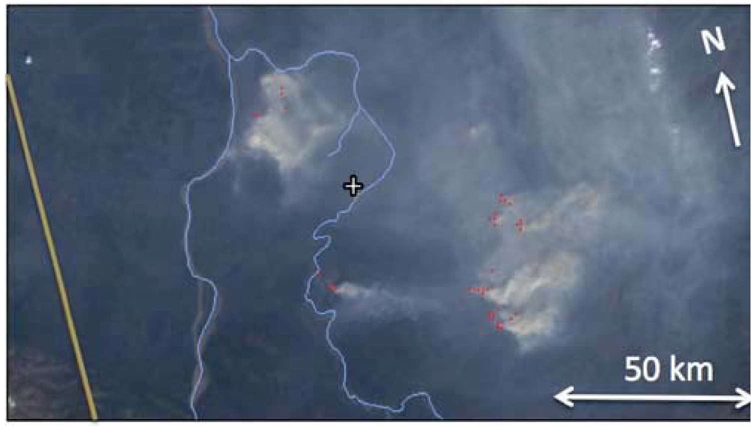
"Connecting diverse terrestrial, emissions, air quality and modelling communities."

Examples from the smoke plume dataset

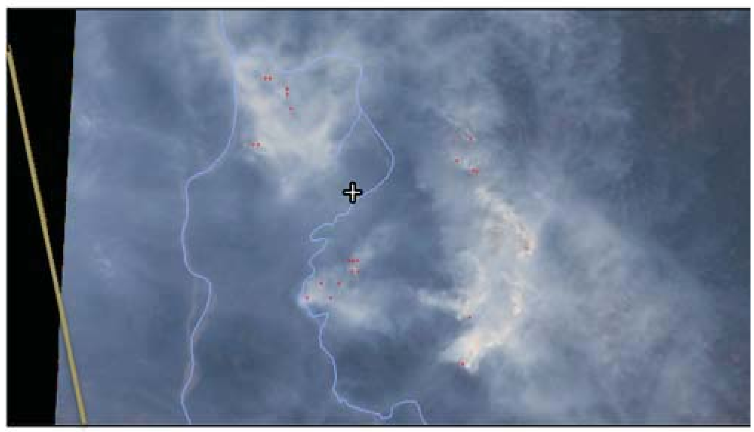
Canadian Smoke Plume Example 1. The 2004 fire year was particularly intense in Alaska and the Yukon. Numerous large fires burned in late June and early July, a few of which are shown in the images of Fig. 4 at right, as MISR passed over the area. Between June 23 and 25 (A and B), under clear skies, several slow-moving fires can be seen. The height of these plumes as determined by MINX is between 1.5 and 3 km on both the 23rd and 25th. The wind is generally from the WNW at 2 to 5 m/s on the 23rd but is relatively stagnant and undirected two days later.

By July 2 (C), under partly cloudy skies, most of the original fire fronts have diminished in strength, and a larger fire has developed between them. This new fire is a duplex structure – a low plume driven by southerly winds beneath a higher plume driven by easterly winds (red arrows). The higher humidity in the cloudy scene increases the potential for condensation of fire-generated water vapor as the plumes rise. The result is that two towering pyrocumulus clouds have formed over the fires (blue arrows), rising to over 9 km.

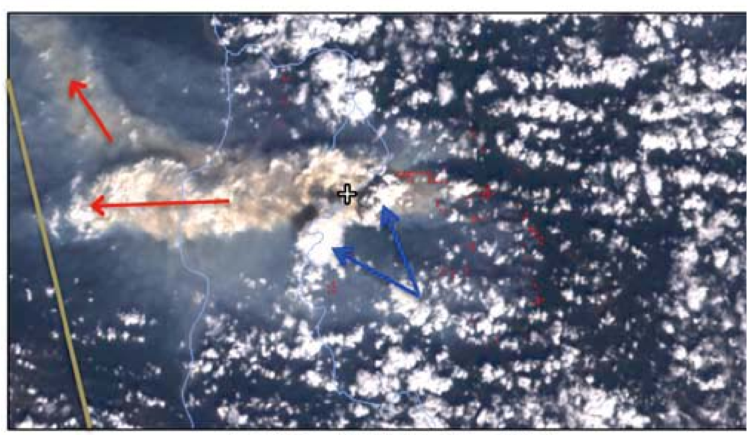
The MODIS 4-micron radiance associated with the plumes in Fig. 4C, interpreted as fire radiative power (FRP, e.g., Kaufman et al., 2003), is 5720 MWatt. Some of this power may be attributable to a fire beneath the pyrocumulus cloud nearer the fire pixels. However, it is likely that most if not all of the thermal radiation from the fire that generated the larger pyrocululus cloud is shielded from



A. MISR orbit 24021, June 23, 2004



B. MISR orbit 24050, June 25, 2004



C. MISR orbit 24152, July 2, 2004

Figure 4. Three images of smoke plumes in the Yukon, Canada, in June and July 2004, captured by MISR's nadir camera, each showing the same geographic region. The brown line is the Canada/Alaska border, light blue lines are rivers and red dots are hot spots detected in the MODIS instrument's 4-micron images. The plus symbol represents a common location near the center of the fires in C (62.29° N, 139.61° W).

The Canadian Smoke Newsletter

2014

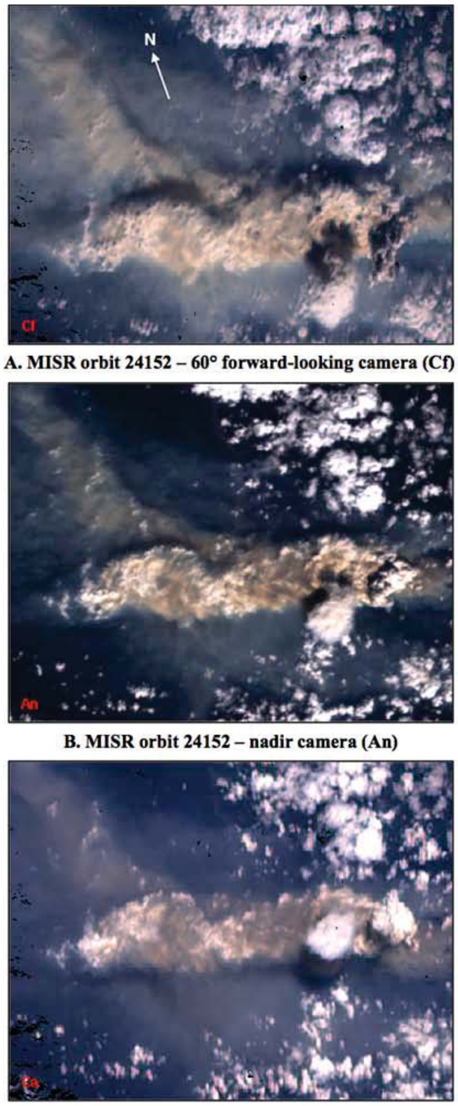
“Connecting diverse terrestrial, emissions, air quality and modelling communities.”

detection by thick smoke.

The three scenes in Fig. 5 at right show the duplex plume from Fig. 4C as imaged by MISR’s 60˚ forward (Cf), nadir (An), and 60˚ aft (Ca) cameras. Nearly vertical columns of aerosol, largely in shadow, connect the pyrocumulus clouds to the plume below on the Cf camera image (Fig. 5A). The clouds’ shadows on the underlying plume and their larger amount of parallax shift reinforce the conclusion that they are higher than the relatively flat mass of the plume. Similar evidence suggests that the north-trending plume lies beneath the other. We also observe that the tops of the pyrocumulus clouds are tilted toward the SW, because their position on the Cf camera is not symmetric with respect to the Ca camera. The top of the pyrocumulus clouds may have entered a regime with northeasterly winds.

The two C camera images in Fig. 5 demonstrate another advantage of multi-angle observations. The aerosol optical thickness is greater in these oblique views through the peripheral smoke than in the nadir view, because the optical path traversed through smoke is greater. This feature is especially useful when retrieving aerosol physical and optical properties (e.g., Martonchik et al., 2009; Kahn et al., 2010).

The MINX retrieval results for these plumes are shown in Figs. 6 and 7. Fig. 6 shows the color-coded heights for the plume in Fig. 5 in map view, and Fig. 7 shows the height and wind profiles. The digital data are also available in the MINX database.



A. MISR orbit 24152 – 60° forward-looking camera (Cf)

B. MISR orbit 24152 – nadir camera (An)

C. MISR orbit 24152 – 60° aftward-looking camera (Ca)

Figure 5. Views of the duplex smoke plume in Fig. 3C from three MISR cameras: A. Cf, B. An, and C. Ca.

Canadian Smoke Plume Example 2.

A pair of large smoke plumes captured by MISR during the ARCTAS field campaign on 30 June 2008 is shown in five camera images in Fig. 8 (next page). A total MODIS FRP of 6524 Mwatt was recorded for the larger plume to the north, and this plume was digitized for MINX height

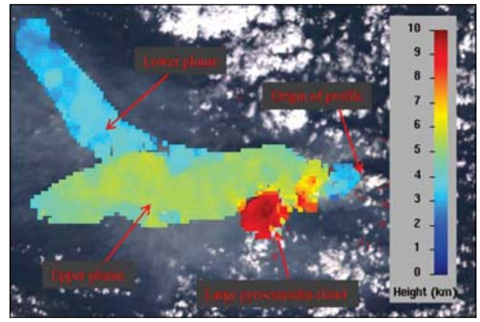


Figure 6. Color-coded, wind-corrected heights in km retrieved by MINX for the duplex plume in Figs. 4C and 5. This is a map-view version of the heights shown in blue in the profile of Fig. 7 (top panel).

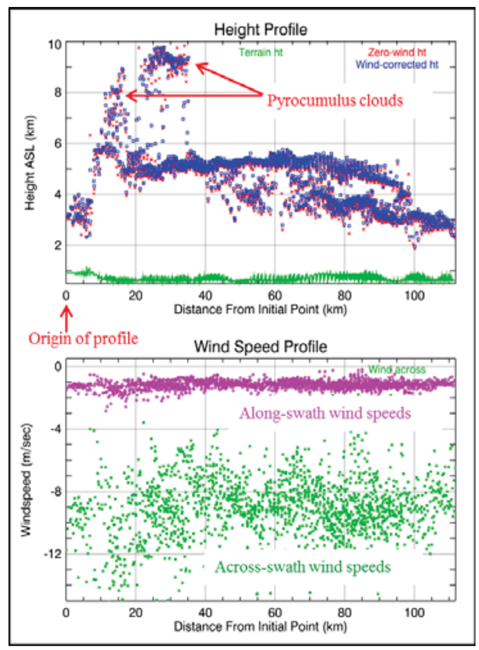


Figure 7. Profiles of height above sea level in km (A) and wind speed in m/s (B) for the duplex plume in Fig. 6 as a function of distance from the initial point digitized. On the height profile, red points are heights uncorrected for wind, blue points are heights corrected for wind and the green line represents the height of the underlying terrain. On the wind profile, green points are wind speeds across-swath and magenta points are wind speeds along-swath.

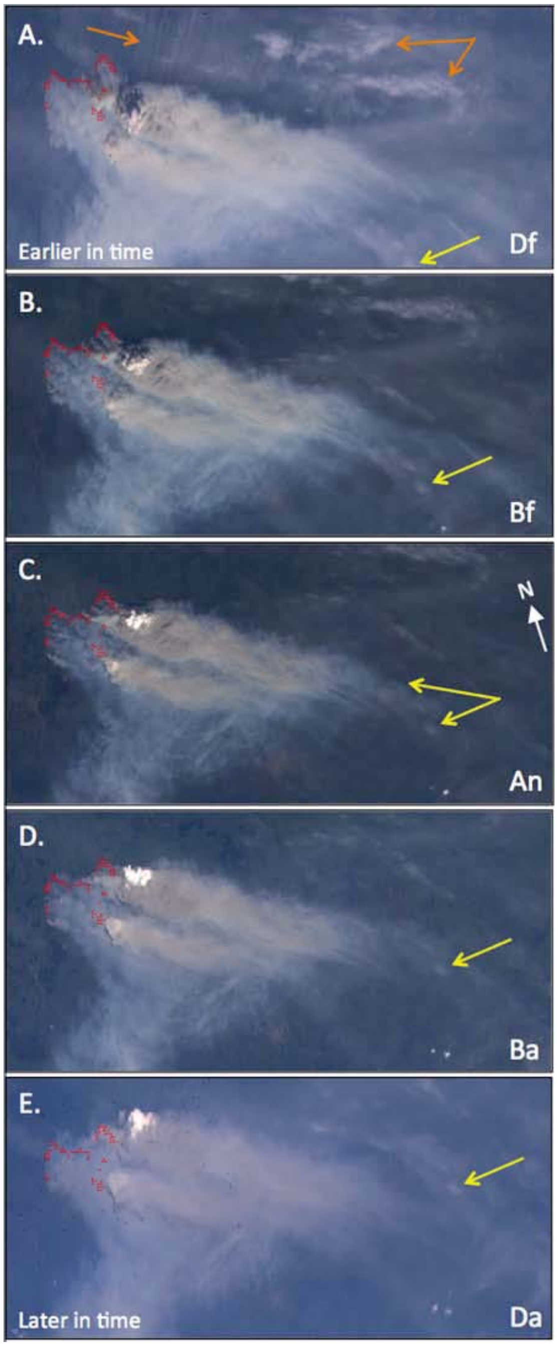


Figure 8. Large plumes on MISR orbit 45397 observed during the ARCTAS campaign in Canada on 30 June 2008. Images are from 5 of MISR’s 9 cameras: A. Df, B. Bf (45° forward-looking), C. An, D. Ba (45° aft-looking) and E. Da. The turbulent clouds at the top of the larger plume are at 55.3 N, 102.50 W.

retrieval. A map of color-coded, wind-corrected heights for this plume is shown in Fig. 9A, and the height profile is given in 9B. Winds of 18 m/s tilt the individual columns of rising smoke about 60° from the vertical. A turbulent mass of smoke capped by a pyrocumulus cloud rises to a height of 6 km over the fire, while the bulk of the plume settles into an equilibrium height of 3 to 4 km. The contrast between the white, water-rich pyrocumulus cloud and the dirty smoke below it is best seen in the bottom two panels of Fig. 8 where reflected sunlight exposes the plume’s southern side.

The absence of color-coded heights toward the SE end of the digitized region in Fig. 9A indicates that no retrievals were obtained there.

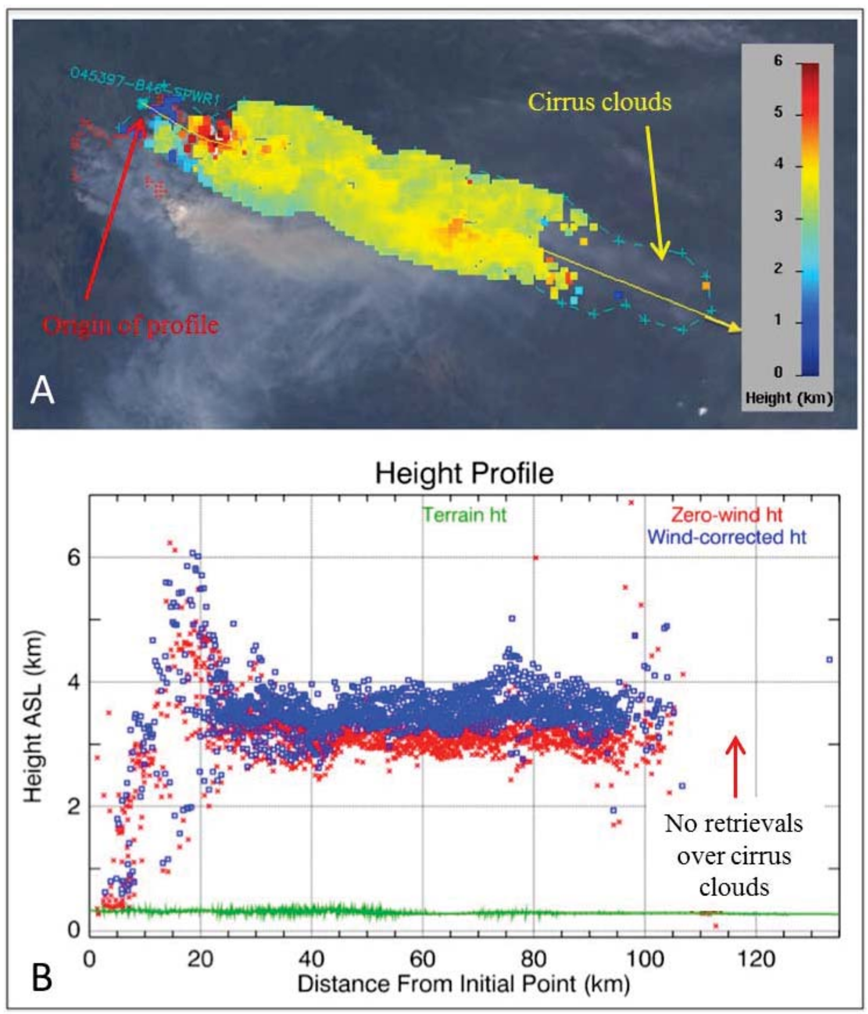


Figure 9. Wind-corrected height retrieval results for the larger plume in Fig. 7 in map view (A) and profile view (B).

Inspection of the camera images shows that what appears to be the tail of the plume on the nadir image (Fig. 8C) is actually cirrus cloud at 11 km altitude (yellow arrows). This altitude was determined in a second retrieval pass, after increasing the maximum height in the MINX height retrieval filter. (Documentation for operating the MINX software is available from the MINX web site.) Other cirrus clouds are indicated by orange arrows on the 70˚ forward (Df) camera image (Fig. 8A). Visual inspection of the multi-angle images is particularly useful in discriminating between signal and noise.

By following the progress of the cirrus cloud forward in time from the Df to the 70˚ aft (Da) camera, we see that it has a component of motion across-swath, toward the right. Parallax does not contribute to motion in the across-swath direction, so we conclude that there is a component of proper motion toward the right. But parallax does contribute in the along-swath direction, so we cannot determine the resultant direction of motion based solely on the changing position of a feature between camera pairs. Structural cues from the smoke are better indicators of true direction of motion, from which the MINX retrieval provides quantitative wind vector constraints.

Applications and Future Work

The five-year MINX North American smoke plume data set has been used to qualitatively assess the fraction of fires that inject smoke above the boundary layer, stratified by land cover type, year, month, boundary layer stability, and MODIS FRP (Val Martin et al., 2010). These data sets have also been applied to quantitatively evaluate the performance of a widely used 1-D plume-rise model, initialized with several common ways of estimating fire area and heat flux (Val Martin et al., 2012). A subset of these plumes was used to demonstrate the complementarity between near-source plume-height maps produced by MISR and downwind aerosol layer height derived from the space-based CALIPSO lidar instrument (Kahn et al., 2008). MINX plume heights combined with CALIPSO layer heights were also used to assess the inter-annual variations in fire plume height over Borneo and Sumatra, and their correlation with El Nino events (Tosca et al., 2011).

Volcanic plumes and dust plumes have been studied with the help of MINX as well. For example, MINX was used to map the heights of the 2010 Iceland volcanic plume eruption (Kahn and Limbacher, 2012), to study the variations in Mt. Etna ash plume injections (Scollo et al., 2012) and to evaluate volcanic plume height determinations by thermal infrared methods (Ekstrand et al., 2013).

Much more extensive application of the MINX tool is possible, and some additional work is planned. For example, the 2008 global plume data, when it is completed, will be used to constrain the AeroCom aerosol transport models (http://aerocom.met.no/Welcome.html), and determine the degree to which applying the observed heights rather than the injection heights commonly assumed in climate models affects the derived smoke aerosol climate forcing. But a primary effort must be made to digitize a larger fraction of the smoke, volcanic, and dust plumes in the more-than-14-year MISR data record. To encourage this, we are developing training tools, so others can contribute to the effort. §

References

Diner, D.J., Beckert, J.C., Reilly, T.H., Bruegge, C.J., Conel, J.E., Kahn, R.A., Martonchik, J.V., Ackerman, T.P., Davies, R., Gerstl, S.A.W., et al., 1998. Multi-angle Imaging SpectroRadiometer (MISR) instrument description and experiment overview, IEEE Trans. Geosci. Remote Sens. 36, 1072–1087.

Ekstrand, A.L., P.W. Webley, M.J. Garay, J. Dehn, A. Prakash, D.L. Nelson, K.G. Dean, and T. Steensen, 2014. A multi-sensor plume height analysis of the 2009 Redoubt eruption, J. Volcan. & Geothermal Res. 259, 170-184.

Kahn, R. A., W.-H. Li, C. Moroney, D. J. Diner, J. V. Martonchik, and E. Fishbein, 2007. Aerosol source plume physical characteristics from space-based multiangle imaging, J. Geophys. Res., 112, D11205, doi:10.1029/2006JD007647.

Kahn, R., Y. Chen, D.L. Nelson, F-Y. Leung, Q. Li, D.J. Diner, and J.A. Logan, 2008. Wildfire smoke injection heights – Two perspectives from space, Geophys. Res. Lett. 35, doi:10.1029/2007GL032165.

Kahn, R.A., B.J. Gaitley, M.J. Garay, D.J. Diner, T. Eck, A. Smirnov, and B.N. Holben, 2010. Multiangle Imaging SpectroRadiometer global aerosol product assessment by comparison with the Aerosol Robotic Network. J. Geophys. Res. 115, D23209, doi: 10.1029/2010JD014601.

Kahn, R.A., and J.A. Limbacher, 2012. Eyjafjallajökull Volcano Plume Particle-

Type Characterization from Space-Based Multi-angle Imaging. Atmosph. Chem. Phys. 12, 9459–9477, doi:10.5194/acp-12-9459-2012.

Kaufman, Y.J., C. Ichoku, I. Giglio, S. Korontzi, D.A. Chu, W.M. Hao, and C.O. Justice, 2003. Fire and smoke observed from the Earth Observing System MODIS instrument - products, validation, and operational use. Int. J. Remt. Sens. 24, 1765-1781.

Martonchik, J.V., R.A. Kahn, and D.J. Diner, 2009. Retrieval of Aerosol Properties over Land Using MISR Observations. In: Kokhanovsky, A.A. and G. de Leeuw, ed., Satellite Aerosol Remote Sensing Over Land. Springer, Berlin, pp.267-293.

Nelson, D.L., Garay, M.J., Kahn, R.A., Dunst, B.A. 2013. Stereoscopic Height and Wind Retrievals for Aerosol Plumes with the MISR INteractive eXplorer (MINX), Remote Sens. 5, no. 9: 4593-4628.

Scollo, S. R.A. Kahn, D.L. Nelson, M. Coltelli, D.J. Diner, M.J. Garay, and V.J. Realmuto, 2012. MISR observations of Etna volcanic plumes. J. Geophys. Res. 117, D06210, doi:10.1029/2011JD016625.

Tosca, M. G., J. T. Randerson, C. S. Zender, D. L. Nelson, D. J. Diner, and J. A. Logan, 2011. Dynamics of fire plumes and smoke clouds associated with peat and deforestation fires in Indonesia, J. Geophys. Res., 116, D08207, doi:10.1029/2010JD015148.

Val Martin, M., R.A. Kahn, J.A. Logan, R. Paugam, M. Wooster, and C. Ichoku, 2012. Space-based observations constraints for 1-D plume-rise models. J. Geophys. Res. 117, D22204, doi:10.1029/2012JD018370.

Val Martin, M., J.A. Logan, R.A. Kahn, F-Y. Leung, D. Nelson, and D. Diner, 2010. Fire smoke injection heights over North America constrained from the Terra Multi-angle Imaging SpectroRadiometer. Atm. Chem. Phys. 10, 1491-1510.